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Condition monitoring and diagnostics of machines — Prognostics —

Part 1: General guidelines

Surveillance et diagnostic des machines — Pronostic —

Partie 1: Lignes directrices générales

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Foreword

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International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 13381-1 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration and shock*, Subcommittee SC 5, *Condition monitoring and diagnostics of machines*.

ISO 13381 consists of the following parts, under the general title *Condition monitoring and diagnostics of machines — Prognostics*:

— *Part 1: General guidelines*

Future parts are under preparation and are intended to outline modelling methods and techniques applicable to prognostics.

Introduction

The complete process of machine condition monitoring consists of five distinct phases, as follows:

— detection of problems (deviations from normal conditions);

— diagnosis of the faults and their causes;

— prognosis of future fault progression;

— recommendation of actions;

— post-mortems.

As far as the prognosis of machine health is concerned (which demands prophecies of future machine integrity and deterioration), there can be no exactitude in the process requiring statistical or testimonial approaches to be adopted. Standardization in prognosis of machine health therefore embodies guidelines, approaches and concepts rather than procedures or standard methodologies.

Prognosis of future fault progressions requires foreknowledge of the probable failure modes, future duties to which the machine will/might be subjected, and a thorough understanding of the relationships between failure modes and operating conditions. This can demand the collection of previous duty and cumulative duty parameters, along with condition and performance parameters, prior to extrapolations, projections and forecasts.

Also, there are a growing number of models for damage initiation and damage progression. Prognosis processes need to accommodate these and future analytical damage models.

As computing power increases and multiple parameter analysis becomes a reality, the ability to predict the initiation of a failure mode is not inconceivable if the initiation criteria, expressed as a set of parameter values for a given mode, are known as well as their future behaviour for a given set of conditions.

Condition monitoring and diagnostics of machines — Prognostics —

Part 1: General guidelines

1 Scope

This International Standard provides guidance for the development of prognosis processes. It is intended

- to allow the users and manufacturers of condition monitoring and diagnostics systems to share common concepts in the fields of machinery fault prognosis,
- to enable users to determine the necessary data, characteristics and behaviour necessary for accurate prognosis,
- to outline an appropriate approach to prognosis development, and
- to introduce prognoses concepts in order to facilitate the development of future systems and training.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 13372, *Condition monitoring and diagnostics of machines — Vocabulary*

ISO 17359, *Condition monitoring and diagnostics of machines — General guidelines*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13372 and the following apply.

3.1
prognosis
estimation of time to failure and risk for one or more existing and future failure modes

3.2
confidence level
figure of merit that indicates the degree of certainty that the diagnosis/prognosis is correct

NOTE 1 It is expressed as a percentage.

NOTE 2 This value is essentially a figure representing the cumulative effect of error sources on the final certainty or confidence in the accuracy of the outcome. Such a figure can be determined algorithmically or via a weighted assessment system.

3.3
root cause
set of conditions and/or actions that occur at the beginning of a sequence of events that result in the initiation of a failure mode

3.4
failure modes effects analysis
FMEA
pre-production design and development process to help determine the ways that a machine could fail, and to assess the associated effects of such failure

NOTE The FMEA procedure is outlined in BS 5760-5.

3.5
failure modes effects criticality analysis
FMECA
process that adds an economic, financial and/or safety component to FMEA to assist in maintenance management decisions

NOTE The FMECA procedure is outlined in IEC 60812.

3.6
failure modes symptoms analysis
FMSA
process based on FMECA that documents the symptoms produced by each mode, and the most effective detection and monitoring techniques, in order to develop and optimize a monitoring programme

NOTE This process is outlined in ISO 13379.

3.7
estimated time to failure
ETTF
estimation of the period from the current point in time to the point in time when the monitored machine is deemed to be in the failed condition

4 Pre-requisite data required

For the general concepts for condition monitoring, see ISO 17359. These form the basis for the prognosis process and its pre-requisites. Prognosis requires collection of documented data covering the following:

a) the total population of plant, machinery and components under observation;

b) all monitored parameters and descriptors;

c) historical operation data, and maintenance and failure data;

d) future operating and maintenance environments, requirements and schedules;

e) initial diagnosis, including identification of all existing failure modes;

f) failure modelling processes that can include statistics, existing and future failure mode influence factors, initiation criteria, and failure definition set points for all parameters, and descriptors;

g) curve fitting, projection and superimposition techniques;

h) alarm limits;

i) trip (shut-down) limits;

j) results of failure investigation;

k) reliability, availability, maintainability and safety data;

l) damage initiation data;

m) damage progression data.

The specific objectives of the collection of reliability data relating to current condition and field performance of machinery are

— to provide for a survey of the actual reliability and, hence, to enable the predicted reliability characteristics of an item to be made and compared with field data and damage models, and thereby to improve future predictions, and

— to provide data for improving the reliability of both the current item and future developments.

The specific objectives of the collection of data relating to current field duties and cumulative duties of machinery are

— to provide for a survey of the relationship between the actual reliability and the work done and, hence, to enable a comparison of damage initiation and progression models with field data,

— to provide data for improving the damage estimation models of both the current item and future developments, and

— to provide data for the extension of the range of applications for damage estimation models.

The specific objectives of the collection of cost data relating to monitoring equipment and usage, production losses, secondary damage losses, maintenance activities and stores inventories of machinery are

— to provide for a survey of the benefit-to-cost ratios of various alternative maintenance actions,

— to improve future maintenance decisions,

— to provide data for reducing the operating and maintenance costs of both the current item and future embodiments, and

— to provide cost data (along with monitored data and performance data, and also with field duty data) for the optimal organization and management of any maintenance operation (on-condition maintenance, scheduled preventive maintenance, corrective maintenance, service personnel, spare parts stores, etc).

5 Prognosis concepts

5.1 Basic concepts

Prognosis is an estimation of time to failure and risk for one or more existing and future failure modes, and is normally intuitive and based on experience. Prognosis is usually effective for faults and failure modes with known, age-related, or progressive deterioration characteristics, the simplist of which is linear. Prognostics are most difficult for random failure modes.

A failure is defined in terms of the monitored parameters/descriptors. Monitoring data on their own is insufficient to produce a prognosis. The general conceptual basics of a prognosis process are

a) to define the end point (usually the trip set point),

b) to establish current severity,

c) to determine/estimate the parameter behaviour and the expected rate of deterioration, and

d) to determine the estimated time to failure (ETTF).

It is important to understand that diagnostics is retrospective in nature in that it is focussed on existing data at a given point in time.

However, prognostics is focussed on the future and, therefore, the following need to be considered:

— existing failure modes and deterioration rates;

— the initiation criteria for future failure modes;

— the role of existing failure modes in the initiation of future failure modes;

— the influence between existing and future failure modes and their deterioration rates;

— the sensitivity to detection and change of existing and future failure modes by current monitoring techniques;

— the design and variation of monitoring strategies to suit all of the above;

— the effect of maintenance actions and/or operating conditions; the conditions or assumptions under which prognoses remains valid.

The general relationship concepts may be graphically represented using causal tree modelling as shown in Figure 1 (FM stands for failure mode).

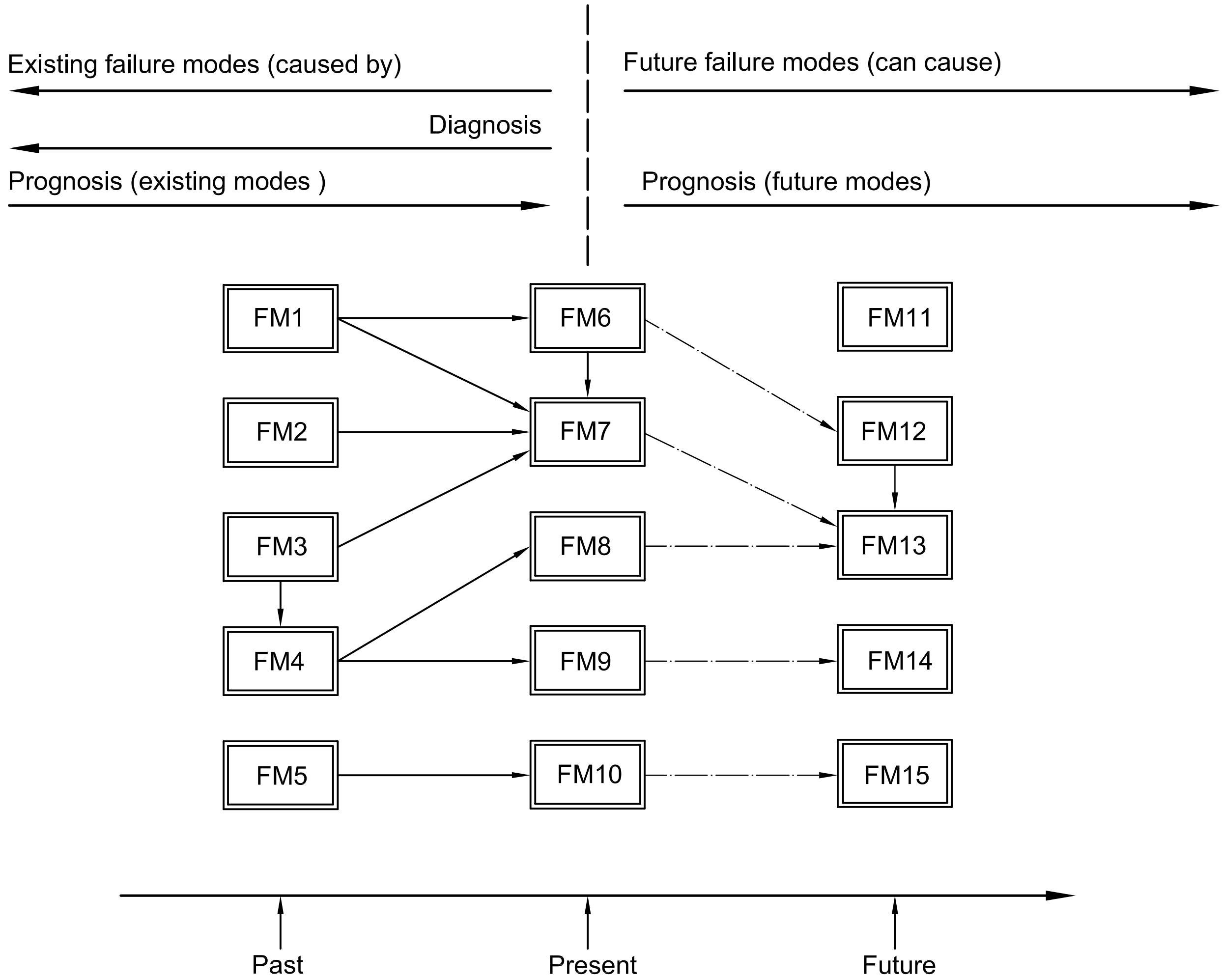
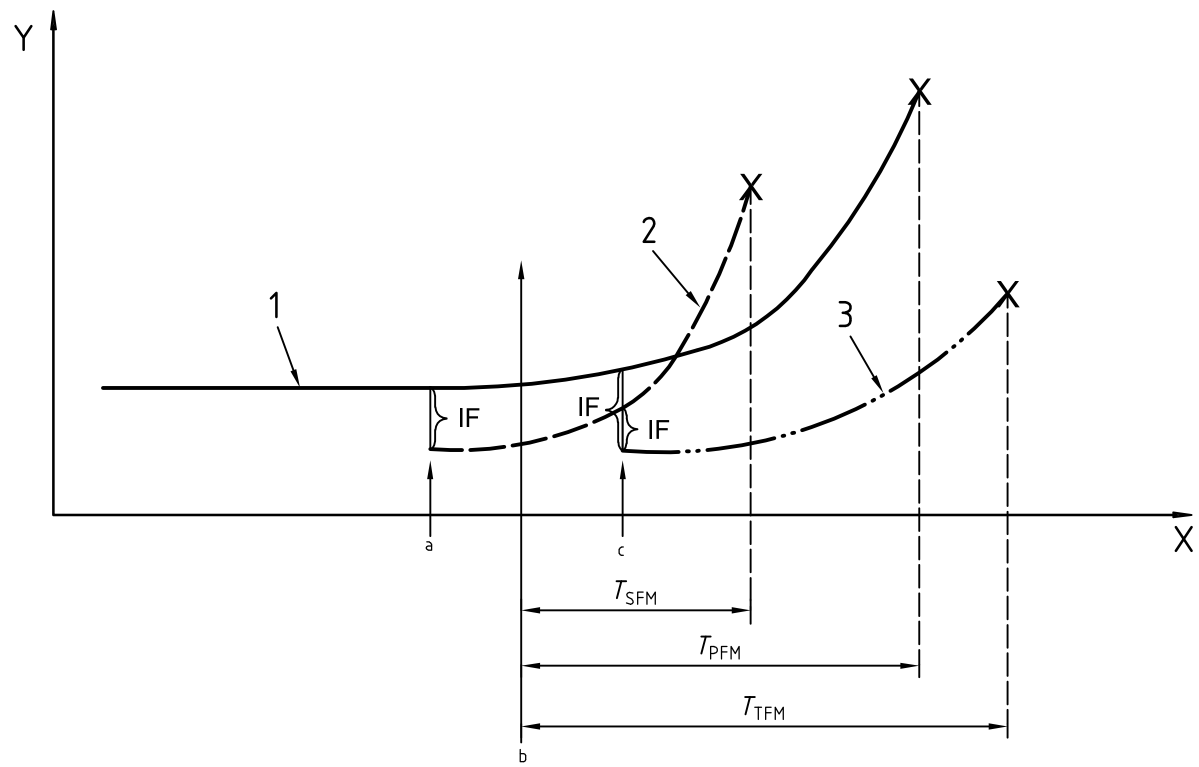


Figure 1 — Causal tree relationships

5.2 Influence factors

Influence factors are parameters that effect the deterioration rate of a failure mode, such as temperature, viscosity, clearance, load and speed. Each influence factor may be considered to be a symptom of an existing failure mode and is represented in Figure 1 by the solid lines that connect existing failure mode trends. Influence factors also have effects on the progression and initiation of other either existing or future faults (see Figure 2).

An example of a situation as described by Figure 2 is where the initial parameter of vibration, due to a fault in a lubricating oil pump bearing (primary failure mode), influences the initiation of a seal failure (secondary failure mode) which has a faster deterioration rate than the bearing. As this seal progresses to failure, the leakage results in a loss of oil delivery pressure, which influences the initiation of an impeller failure in the pump (tertiary failure mode), which has a slower deterioration rate.



Key

X time

Y severity of parameter

1 PFM: primary failure mode (solid line)

2 SFM: secondary failure mode (dashed line)

3 TFM: tertiary failure mode (dotted line)

IF is the influence factor

T_{PFM} is the estimated time to failure of the PFM

T_{SFM} is the estimated time to failure of the SFM

T_{TFM} is the estimated time to failure of the TFM

[a] Time of secondary failure mode initiation.

[b] Present time.

[c] Time of tertiary failure mode initiation.

Figure 2 — Influence factors

5.3 Setting alert, alarm and trip (shut-down) limits

The failure definition set point for a parameter/descriptor is the final value that it reaches at the point in time when the item fails. This value is normally determined historically from failure history.

The trip set point, however, is the parameter/descriptor value at which the machine is shut down and is normally less than its failure set point. This value is normally determined from standards, manufacturers' guidelines and experience. This is the value normally used to define the failed condition. However, this value does not usually reflect the fully failed condition, due to its lower set point required to prevent consequential damage or catastrophic failure.

Alert and alarm limits are normally set at a value less than the trip set point. This value is usually based on the maintenance lead time required. However, the following parameters should be known before deciding such alert values:

a) the confidence level of the prognosis;

b) future production requirements;

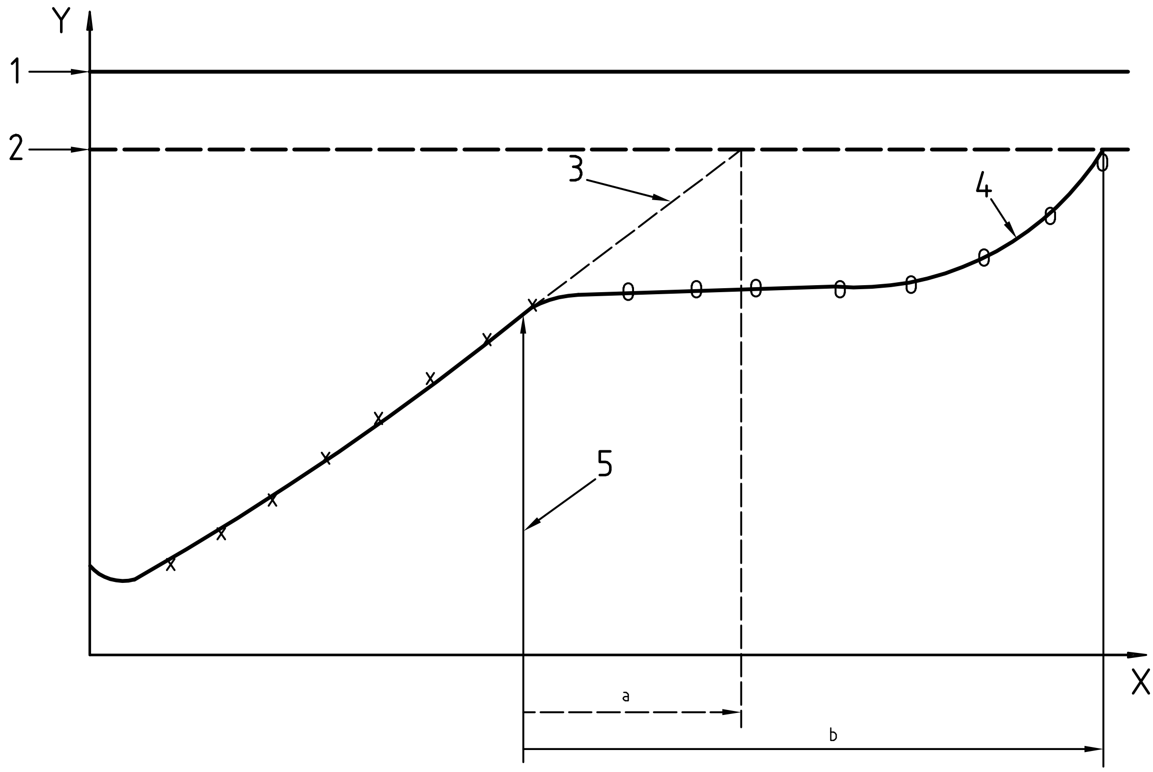
c) delivery lead times for spare parts;

d) maintenance planning lead time required;

e) scope of work required to rectify faults;

f) trend extrapolation and projection.

The basic difference between trend extrapolation and trend projection is that projection requires the estimation of future data followed by curve fitting, whereas an extrapolation curve is fitted only to existing data (see Figure 3). Most current curve fitting is extrapolative in nature, in that a curve is extrapolated using existing data points.



Key

X time

Y value of parameter

x known points

O behaviour points

1 failure value

2 trip set point

3 extrapolation

4 projection

5 present time

[a] ETTF (extrapolation).

[b] ETTF (projection).

Figure 3 — Extrapolation versus projection

This process requires that the behaviour of a set of parameters is understood for a given failure mode set and given conditions. Trend projection requires mathematical equations expressing the rate of change of a variable that describes the deterioration of a given failure mode under given conditions.

An example of the above concept would be an equation that describes the rate of change of an overall acceleration value for a plummer block mounted 6 316 deep groove ball bearing, running at 3 000 r/min, lubricated by a 220 cSt viscosity grade mineral oil, running at 80 °C. If such equations are known, then trend projections result in far more accurate prognoses than extrapolations, as the future data behaviour is known.

5.4 Multiple parameter analysis

Prognosis can be performed using a single parameter or multiple parameters. Multiple parameter analysis is the simultaneous display of all data within the one system. This concept is paramount to prognostics in that the relationship between parameters can be observed, not just the parameters themselves. This is particularly important for different yet possibly interdependent parameters, such as bearing temperature and oil viscosity (see Figure 4).

One principle of multiple parameter analysis is that the technique must trend both parameters (unfiltered/unprocessed variables) and descriptors (filtered/processed data) simultaneously. The use of narrow band filters allows spectrums to be divided into discrete elements of which the band amplitude can then be used for multiple parameter analysis trending. The failure definition set point for each narrow band is the assigned maximum allowable amplitude for each band.

This allows, for example, each narrow band amplitude to be plotted against other vibration descriptors, oil analysis results, process parameters and performance values, in order to identify and establish relationships between each of them.

The difficulty with the presentation of multiple-parameter analysis is that each variable has a different unit of measurement. This is compounded if the variable can attain the same value more than once during the life of the component (see Figure 4). Multiple-parameter analysis trending and alarming is also made difficult when the value of the variable in the failed condition is zero (e.g. flow or pressure).

One key difference between standard multiple-parameter analysis for monitoring and multiple-parameter analysis for prognosis is that prognosis requires a common severity axis.

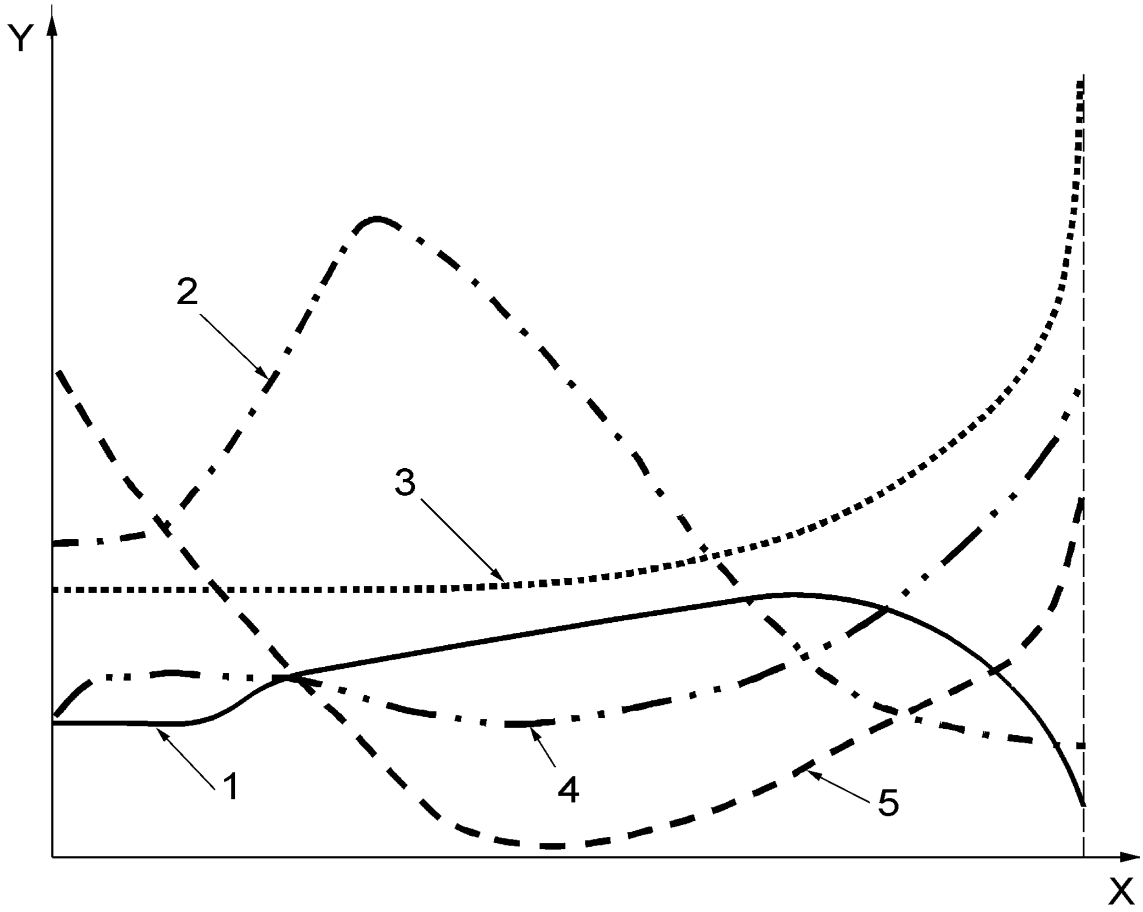
For simplicity, this can be set to percentage of life usage, where 0 % life used occurs when the machine has not been operated and 100 % life used occurs when the machine is in the failed condition. At this stage, data that may approach zero when the machine is in the failed condition (such as flow or pressure) must be inverted to reflect the "% Life Usage" relationship.

It is important when carrying out prognosis based on multiple-parameter analysis that, for each parameter and/or descriptor being used, the following are known:

— the start value representing 100 % asset life or new condition;

— the end value representing 0 % asset life or failed condition;

— how the parameter and/or descriptor behaviour reflects the failure mode development and associated reduction in asset life.



Key

X independent reference value

Y value of parameter

1 parameter 1

2 parameter 2

3 parameter 3

4 parameter 4

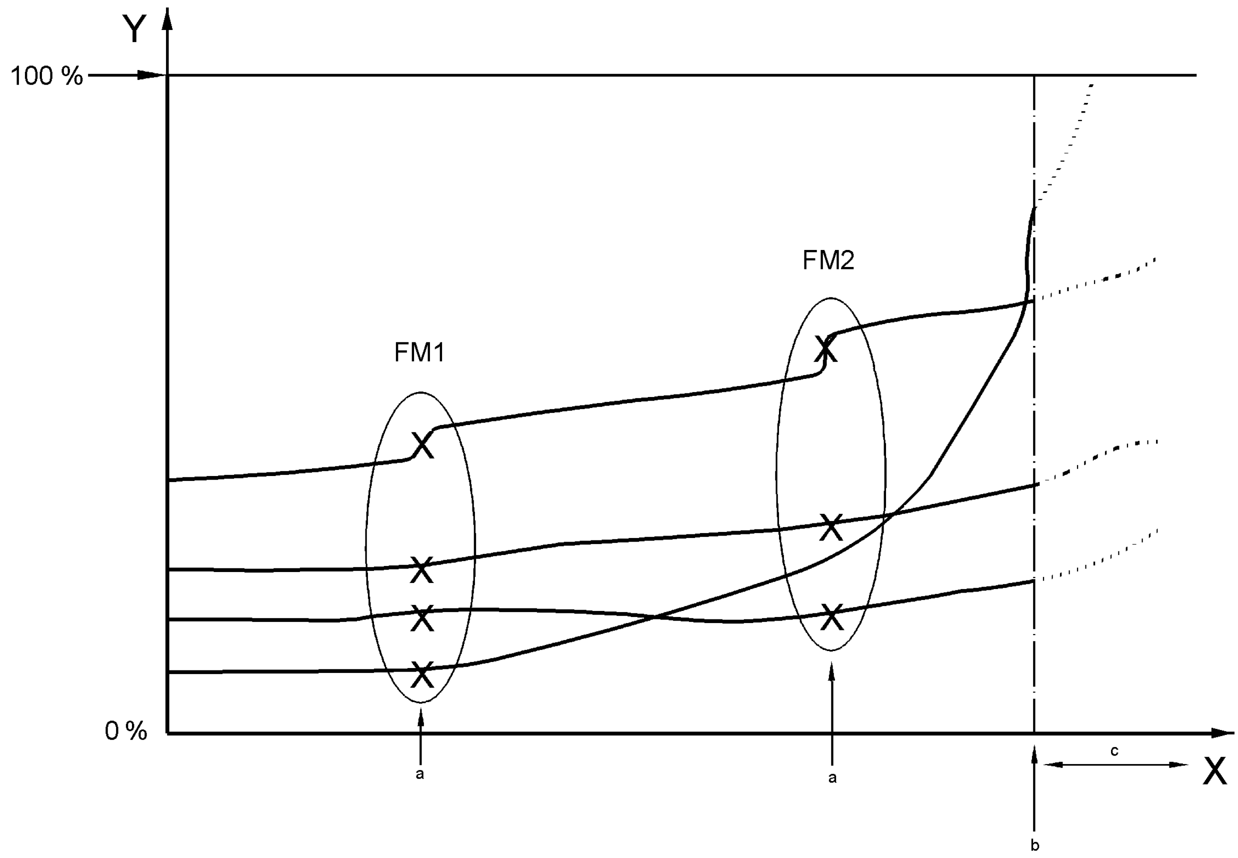
5 parameter 5

Figure 4 — Example of multiple-parameter display

5.5 Initiation criteria

For future failure modes, these influence factors must first be described as initiation criteria in that the same parameter can be both an influence factor for an existing mode and an initiation criteria for a future mode. This introduces the concept of initiation criteria data sets, where the root cause of a failure mode can be described in terms of a set of different parameter values that either directly or indirectly measures its occurrence (see Figure 5).

Direct measurement can take such forms as valve position, whereas the indirect method measures a symptom of a change such as temperature.



Key

X time

Y percent life usage (100 % = failed; 0 % = full life)

FM1 action

FM2 condition and action

a Initiation criteria set.

b Present time.

c Estimated extrapolation.

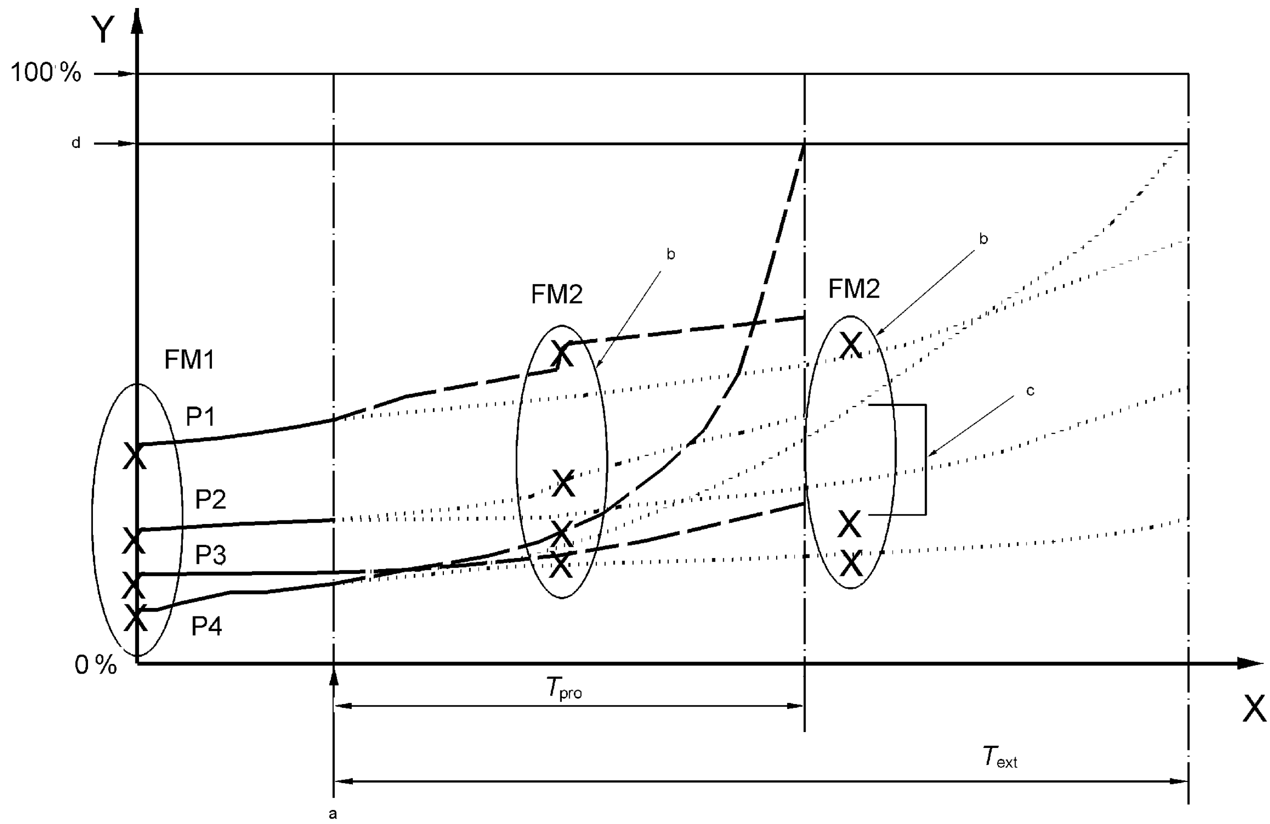
Figure 5 — Criteria for failure mode initiation

5.6 Prognosis of failure mode initiation

The initiation of a failure mode should always be traced back to its root cause. The root cause in itself can be described in terms of a set of conditions and actions whereby a condition will generally produce a steady rate of change and an action will usually result in a step change (see Figure 5).

Using multiple-parameter analysis techniques, the evidence of actions, conditions and their interdependence can be readily observed. Failure mode initiation criteria, expressed as a set of values for all monitored parameters, may therefore be used to trigger alarms, indicating that a failure mode has been initiated, once this set of values has been achieved or exceeded.

Prognosis of failure mode *initiation* may, therefore, be achieved given a known initiation criteria set and trend projection techniques. The accuracy of the prognosis will depend greatly on whether or not trend extrapolation or projection is used (see Figure 6).



Key

X time

Y percent life usage (100 % = failed; 0 % = full life)

—— projection

...... extrapolation

P parameter

FM failure mode

T_{pro} ETTF (projection)

T_{ext} ETTF (extrapolation)

[a] present time

[b] initiation criteria

[c] exceedence

[d] trip set point

Figure 6 — Initiation prognosis: Projection versus extrapolation

This method requires a thorough understanding of

— failure mode initiation criteria, which can be historically and/or statistically generated over time,
— sufficient multiple-parameter analyses of a wide set of monitored parameters,
— thorough understanding of the relationships between, and interdependence of, failure modes,
— known operating conditions at the time of failure mode initiation, and
— the behaviour of parameters under varying conditions and influences.

6 Failure and deterioration models used for prognostics

6.1 Modelling concepts for failure mode behaviour

Prognosis requires a methodology that conceptually includes the use of, for example, the following existing failure mode behaviour models:

a) failure mode effect and criticality analyses (FMECA);

b) causal/fault tree analyses;

c) risk and hazard assessment methods;

d) damage initiation and progression models;

e) trend extrapolation and projection methods.

These methodologies provide the source data on failure modes and relationships, severity and risk, rates of deterioration and prognosis data.

Once a fault has been detected and/or diagnosed, one of the main issues is to estimate the time to failure (ETTF). Although the ETTF is generally determined by expert opinion, several models of reasoning may be applied. An expert normally uses intuitive and/or empirical methods for estimating the ETTF and will use some elements of each model.

Several sources of information are generally used to determine the ETTF, such as

— monitoring data,
— test data,
— life duration data,
— reliability/availability data,
— manufacturers' data,
— previous case histories, and
— operational data.

6.2 Modelling types

Although prognosis is usually performed by an expert, different types of models exist and may be used to varying degrees. Classical reasoning models used for diagnosis may be applied for prognosis. The depth of analysis is more important, in this case, as future events are hypothesized.

7 Generic prognosis process

7.1 Prognosis confidence levels

The generic condition monitoring process, including prognosis, is outlined in Annex A. Within this flow diagram there are several concepts requiring sub-processes, such as determining confidence levels and the iterative confirmation process.

A confidence level is a figure of merit (percentage) that indicates the degree of certainty that the diagnosis/prognosis is correct.

This value is essentially a figure representing the cumulative effect of error sources on the final certainty or confidence in the accuracy of the outcome. Such a figure can be determined algorithmically or via a weighted assessment system.

Such a system should incorporate a weighted assessment of the negative impact of errors or lack of information associated with, but not limited to, the following:

a) maintenance history;

b) design and failure mode assessment;

c) analysis technique parameters used (sensitivity to detection and change);

d) severity limits used;

e) measurement interval;

f) database set-up;

g) data acquisition;

h) severity assessment processes;

i) trend assessment;

j) diagnosis process;

k) prognosis process.

It should be noted that assigned weightings for each confidence factor criterion can vary between diagnoses and prognoses, since each criterion can have a different bearing on the outcome for each process. An example of a simple determination is given in Annex B.

7.2 Prognosis process

7.2.1 General

The generic process involves four basic phases: pre-processing, existing failure mode prognosis, future failure mode prognosis, and post-action prognosis. The process is generally sequential, as detailed in 7.2.2 to 7.2.5.

7.2.2 Pre-processing

The process is as follows.

a) Carry out a diagnosis in order to identify all existing failure modes.

b) Identify influence factors between existing failure modes.

c) Define failure definition and trip set points for all current symptoms, parameters and descriptors.

d) Determine potential future failure modes, their initiation criteria and failure definition set points.

e) Select a suitable failure mode model (see Annex D).

7.2.3 *Existing* failure mode prognosis process

The process is as follows.

a) Assess the severity of all measured failure modes and their parameters/descriptors against their trip set points.

b) Project all failure mode parameter and descriptor trends to their trip set points.

c) Select the existing failure mode with the shortest ETTF.

d) If possible, execute an iterative confirmation process until the confidence in the ETTF is acceptable.

7.2.4 *Future* failure mode prognosis process

The process is as follows.

a) Assess future failure mode initiation criteria and determine the most probable future failure modes.

b) Determine the influence factors between all existing and future failure modes.

c) Estimate the initiation point, trends and ETTF for each future failure mode, taking into account all influence factors and trip set points.

d) Select the most critical future failure mode with the shortest ETTF and develop an "initial prognosis" with associated confidence level and validity conditions.

There may be a requirement to produce one or more action options. The simplest action that can be taken in certain circumstances, such as low criticality machines, is to carry out no immediate action. The prognosis for this option is identical to the "initial prognosis".

The initial prognosis should state the critical *existing* failure mode, ETTF and confidence level, and the critical *future* failure mode, ETTF and confidence level if there is a high risk of occurrence and/or impact risk. A statement detailing the conditions under which the prognosis is valid should accompany the prognosis.

7.2.5 Post-action prognosis

The process is as follows.

a) Identify one or more actions that will retard, halt or eliminate the progression of the critical existing failure mode and prevent the initiation of future failure modes.

b) Revise the failure model and repeat the prognosis process [steps 7.2.2 b) to 7.2.4 b) inclusive], taking into account the effects of any maintenance action.

c) Develop a post-action prognosis with associated confidence level and validity conditions.

It may be of benefit to consider interim maintenance actions that alleviate the failure mode progression and prevent the occurrence of future modes. These interim actions are normally non-intrusive (e.g. re-greasing a bearing).

An ultimate solution option should also be considered. These actions are normally intrusive (e.g. overhauling the machine or replacing a part). The post-action prognosis for this option is normally based on historical reliability data.

The post-action prognosis should state the critical *existing* failure mode, ETTF and confidence level (post-interim-maintenance action), and the critical *future* failure mode, ETTF and confidence level if there is a high risk of occurrence and/or impact risk.

A statement detailing the conditions under which the prognosis is valid should accompany the prognosis.

The recommendation of any action (nil, interim or final solution) will essentially be a risk-based decision process taking into account financial, environmental, safety and other forms of risk or impact.

8 Prognosis report

A complete prognosis report should include the diagnostic report requirements stated in ISO 13379 and, as a minimum, the following:

a) machine identification code or number;

b) machine description;

c) statement of the operating condition of the machine at the time of measurement;

d) a list, or reference to an available list, of all measurement points, parameters and measurement instrumentation used during the prognosis process;

e) the diagnosis, inclusing all identified failure modes;

f) the initial prognosis (existing and future modes), confidence level, validity conditions and associated risk (no action);

g) any additional tests required to increase confidence levels;

h) any recommended action, its associated prognosis (existing and future modes), confidence level, validity conditions and associated risk;

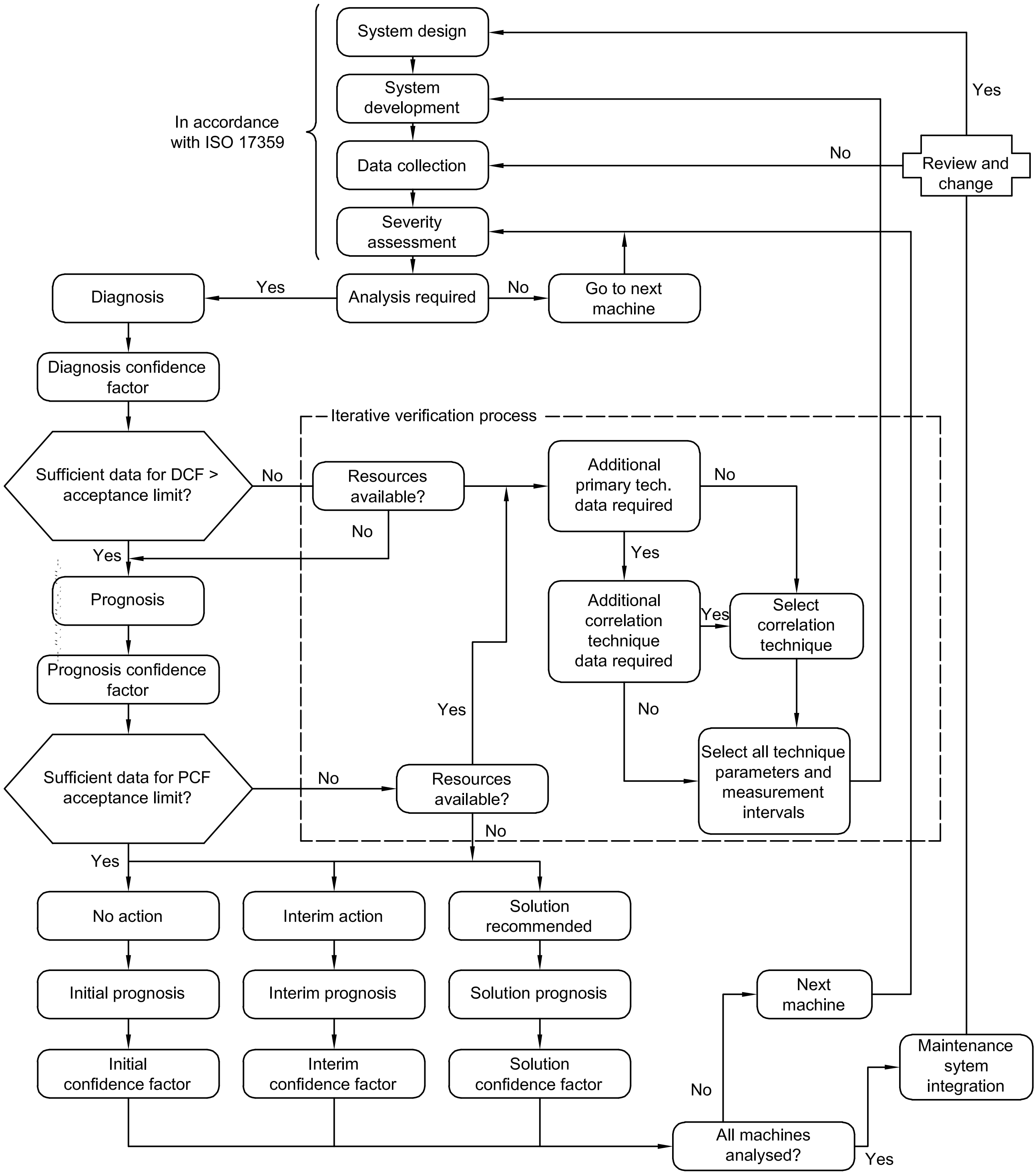
i) any alternative action, its associated prognosis (existing and future modes), confidence level, validity conditions and associated risk.

In general, the report may consist of a initial table of exceptions, listing only those machines or components that are in alarm, that details the facts in brief. The section may precede a more detailed section that expands on each individual alarm condition, the diagnoses, any additional tests required, any recommended and alternative actions, possible future failure modes and their associated prognoses, and any other pertinent information.

It may also be of benefit to include a severity indicator and a trend indicator in any tabulated section, as this allows for immediate recognition of severe and/or changing conditions, and situations where the condition is approaching the alarm state and may become so before the next set of readings.

Annex A
(normative)

Condition monitoring flow chart



Annex B
(normative)

Example of the determination of the confidence level of a prognosis

Process activity step	Error sources	Weighting	Assigned confidence value %	Resultant confidence level %
1	**Maintenance history**	0,15		
2	**Design and failure mode analysis**	0,10		
3	**Analysis technique parameters used**	0,15		
4	**Severity limits used**	0,10		
5	**Measurement Interval**	0,10		
6	**Database set-up**	0,5		
7	**Data acquisition**	0,5		
8	**Severity assessment process**	0,5		
9	**Diagnosis process**	0,10		
10	**Prognosis process**	0,15		
OVERALL CONFIDENCE LEVEL				
NOTE Confidence level is the sum of the weighting and the assigned confidence value.				

Annex C
(informative)

Failure modelling techniques

C.1 Mathematical/life usage models

These are

— behaviour,

— statistical,

— probabilistic, and

— artificial neural network.

C.2 Life expectancy model

The life duration of individual components in a machine can been estimated with respect to the risk of deterioration during inspection and the risk of failure during operation, and can be

— reliability based, and

— deterioration based (statistical, deterministic, expert opinion, equations, tests, FEM, damage models).

C.3 Knowledge-based models

These are

— rule-based symptom/fault model,

— causal tree model (described in ISO 13379), and

— case-based reasoning.

The principle for the latter is to use the similarity between the observed situation and case(s) already known and solved (e.g. this fault resembles other cases). This model needs a learning phase based on good experience, i.e. based on several well-described cases.

C.4 Mathematical models

These are

- behaviour (the principle is to model the behaviour using physical laws; modelling may be quantitative or qualitative),
- statistical (a Pareto approach that uses statistical histograms to evaluate the probability of occurrence of one or more failure modes),
- probabilistic (a modelling process that calculates the probability of a failure mode based on the probabilities of the initiating failure modes),
- neural network (a computer-based system that uses neural network in order to compute probability of occurrence).

NOTE The basic idea is to compute an estimated output from a numerical representation of a current state. As for case based modelling, the learning phase is essential.

C.5 Reliability models

These models provide reliability-related information as probabilistic values with respect to time. Computation on these functions can provide mean time to failure (MTTF) values.

Weibull analysis may be used to take into account failure rate increase when components become old or in cases of “infant mortality” (i.e. failures that occur in early stages of an asset’s life).

Reliability factors may be adjusted with respect to monitoring data and operating conditions. This enables reliability factors to be individualized for a given machine.

C.6 Deterioration models

These are used to estimate the deterioration (damage) initiation and progression (e.g. wear, cracks, corrosion).

They may be modelled with several states of deterioration, based on previous inspection results on similar machines. These models may be coupled with “good behaviour models” to predict future deterioration.

C.7 Model validation

The purpose of this model is to associate a known and/or quantified state of deterioration observed by inspection with the condition predicted by the modelling process. This validation process may also include verifying the magnitude of any measured parameters/descriptors with the physical damage evidence.

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